REQUEST FOR AN EMI R&D PROJECT 2027–2029

Country/Organisation: Italy

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Project Title: Bistability of AMOC in EC-Earth3-ESM

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** …………..	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2027	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for project year:		**2027**	**2028**	**2029**
High Performance Computing Facility	[SBU]	25,000,000 SBU	25,000,000 SBU	
Graphics Processing Unit Cluster-A	[GBU]			
Graphics Processing Unit Cluster-B	[GBU]			
Accumulated data storage (total archive volume)[2]	[GB]	48 TB	96 TB	

EWC resources required for project year:		**2027**	**2028**	**2029**
Number of vCPUs	[#]			
Total memory	[GB]			
Storage	[GB]			
Number of vGPUs[3]	[#]			

[1] The Principal Investigator will act as contact person for this EMI R&D Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.
[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.
[3]The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

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Extended abstract

Overview

This project investigates the stability and potential tipping behaviour of the Atlantic Meridional Overturning Circulation (AMOC) under freshwater perturbations and global warming using the EC-Earth3-ESM Earth System Model. While theory suggests that the AMOC may exhibit tipping points and hysteresis, evidence from comprehensive climate models remains inconclusive, with large inter-model differences in whether the AMOC recovers after strong freshwater forcing.

Recent coordinated experiments (NAHosMIP and TIPMIP-OCEAN) show that EC-Earth3-ESM generally recovers from moderate freshwater perturbations under both pre-industrial and +2°C warming conditions, but collapses irreversibly under stronger forcing, indicating the possible existence of a critical freshwater threshold separating reversible and irreversible AMOC responses.

The main objective of this project is to identify this threshold and understand the physical mechanisms controlling AMOC hysteresis in EC-Earth3-ESM. This will be achieved through a set of idealised freshwater hosing experiments spanning a range of forcing strengths and background climate states, including recovery phases after forcing removal. The results will improve understanding of AMOC stability, help interpret intercomparison results, and reduce uncertainty in projections of future AMOC change.

1. Introduction

1.1 Scientific Context

The Atlantic Meridional Overturning Circulation (AMOC) is a key component of the climate system and is projected to weaken under anthropogenic climate change. Theory and conceptual models suggest that the AMOC may exhibit tipping behaviour, with a critical threshold beyond which recovery becomes difficult even if the forcing is removed, resulting in hysteresis or quasi-irreversible changes. While such behaviour has been demonstrated in simplified models, evidence from comprehensive climate models remains less conclusive. One possible reason is that biases in the mean state of climate models may affect the feedbacks controlling AMOC stability, tipping behaviour, and recovery (Weaver et al., 2012; Mecking et al., 2017).

A common approach to investigate AMOC stability in comprehensive climate models is through idealised freshwater hosing experiments, in which freshwater is artificially added to the North Atlantic to simulate the effects of Greenland Ice Sheet melting. These experiments perturb deep-water formation and allow the assessment of AMOC sensitivity, potential collapse, and recovery.

The North Atlantic Hosing Model Intercomparison Project (NAHosMIP; Jackson et al., 2023) was designed to systematically assess the AMOC response to freshwater perturbations across CMIP6-class climate models. The protocol consists of applying freshwater hosing in the North Atlantic and Arctic Ocean for a fixed period, followed by a recovery phase after the forcing is removed. The results reveal that half of the participating models do not recover their AMOC following a 0.3 Sv freshwater perturbation, whereas the other half return to a state comparable to their pre-hosing conditions. EC-Earth3, whose simulations were performed by our group, belongs to the latter category.

Importantly, the contrasting AMOC recovery behaviour across models cannot be explained by differences in ocean model resolution, subgrid-scale parameterisations, or commonly used indicators of AMOC stability, such as the strength of the salinity-advection feedback, the location of deep convection sites, or the position of the intergyre boundary (Jackson et al., 2023). This suggests that key processes controlling AMOC resilience and recovery remain poorly understood. Identifying these processes is crucial for improving confidence in future AMOC projections and assessing the risk of crossing critical thresholds under climate change.

1.2 Current status

The Tipping Points Modelling Intercomparison Project (TIPMIP; Winkelmann et al., 2025) is an international community initiative aimed at addressing key knowledge gaps in tipping dynamics of the Earth system. Within TIPMIP, the ocean domain (TIPMIP-OCEAN; Swingedouw et al., 2026) defines a coordinated set of idealised experiments designed to assess the sensitivity of the AMOC to combined global warming and freshwater perturbations, as well as its potential recovery after the forcing is removed. The protocol is intended for implementation in CMIP7-class models, but is also applicable to CMIP6+ configurations.

A key element of the experimental design is Experiments C, which extends the NAHosMIP framework by applying freshwater hosing perturbations under both pre-industrial and +2°C global warming level (GWL) background states. This setup allows for a systematic investigation of how climate change modifies AMOC stability, tipping behaviour, and reversibility.

Within this framework, we have performed the Experiments C using the EC-Earth3-ESM Earth System Model. Consistent with previous NAHosMIP results, EC-Earth3-ESM shows a recovery of the AMOC after the cessation of a 0.3 Sv freshwater perturbation, both under pre-industrial (Tier 1) and +2°C GWL (Tier 2) background climates. This indicates a strong resilience of the overturning circulation to freshwater forcing in this model configuration.

However, when subjected to a substantially larger freshwater forcing (3 Sv), the AMOC undergoes a pronounced collapse and, importantly, does not recover after the forcing is removed, remaining in a collapsed state throughout the post-hosing period (Figure 1). This behaviour suggests the existence of a critical threshold in freshwater forcing strength that separates reversible from irreversible AMOC responses in EC-Earth3-ESM.

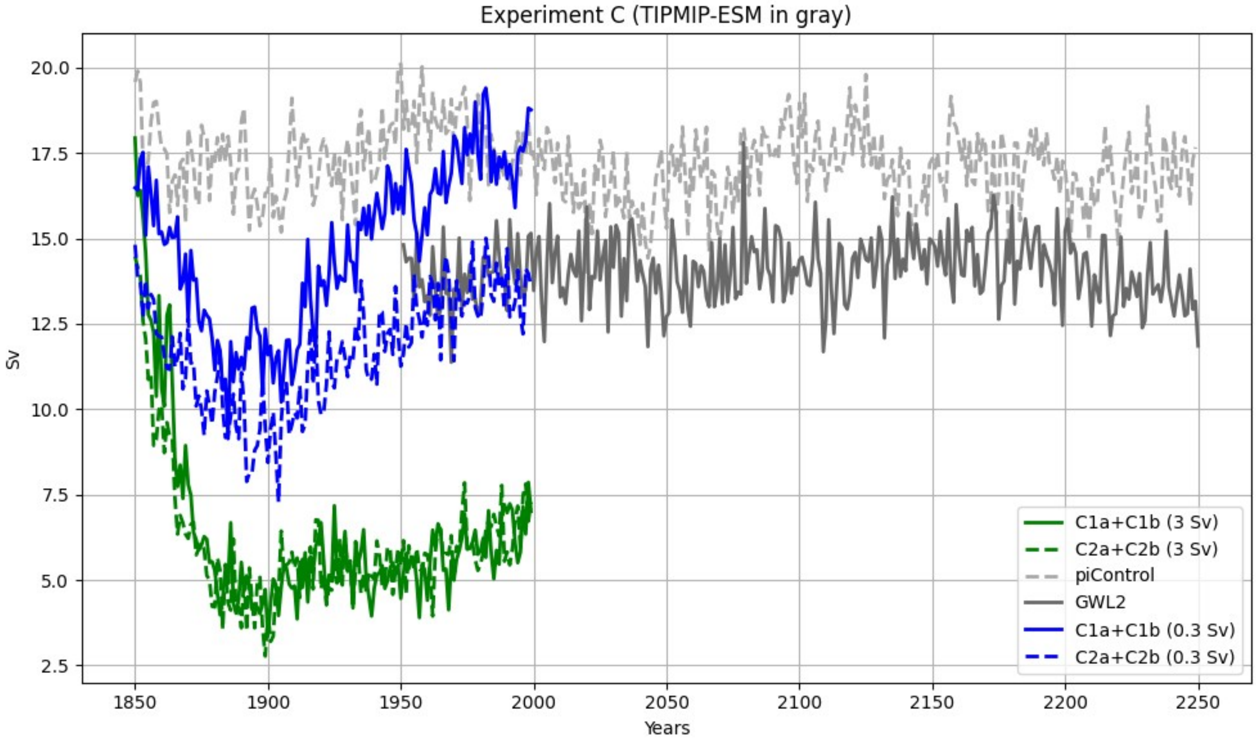

Figure 1: Timeseries of the AMOC index at 26N for the Experiments C performed with EC-Earth3-ESM to participate in TIPMIP-OCEAN. Experiments with freshwater hosing strength of 0.3 Sv (in blue) and 3.0 Sv (in green), and the background climates (in gray) are displayed. Dashed lines are the experiments with pre-industrial background climate and solid lines with 2 GWL background climate.

The results therefore indicate a strongly nonlinear response of the AMOC, characterised by a transition between recovery and persistent collapse depending on the magnitude of the perturbation. Identifying the physical mechanisms that control this threshold behaviour is essential for understanding AMOC stability under extreme forcing and for reconciling differences between model responses within TIPMIP and related intercomparison projects.

1.3 Objective and expected contributions to the field

Building on our previous contributions to NAHosMIP and TIPMIP-OCEAN using EC-Earth3 and EC-Earth3-ESM, this project aims to investigate the existence and nature of a critical freshwater forcing threshold in the North Atlantic that governs the onset of AMOC hysteresis in EC-Earth3-ESM.

In particular, we seek to determine whether a well-defined transition in freshwater forcing strength separates a regime of reversible AMOC weakening from a regime of irreversible collapse, and to characterise the associated dynamical mechanisms. By analysing the model response across a range of perturbation strengths, we aim to identify the processes that control AMOC bistability and recovery behaviour in this model configuration.

The expected outcome is an improved mechanistic understanding of AMOC stability in EC-Earth3-ESM, which will help to interpret its behaviour within intercomparison projects and contribute to reducing uncertainty in projections of AMOC stability under future climate change.

2. Methodology

2.1 The Earth System Model

The model used in this study is EC-Earth3-ESM (Döscher et al., 2022), a fully coupled Earth System Model developed by the European EC-Earth Consortium for participation in the Coupled Model Intercomparison Project (CMIP6 and CMIP7). EC-Earth3-ESM extends the physical climate configuration of EC-Earth3 by incorporating interactive representations of the carbon cycle, terrestrial biosphere, and cryosphere, enabling a comprehensive simulation of coupled atmosphere–ocean–land–ice–carbon system interactions.

The atmospheric and land components are based on the Integrated Forecasting System (IFS cycle 36r4), coupled to the NEMO ocean general circulation model (version 3.6), including the LIM3 sea-ice model. Terrestrial ecosystem dynamics are represented by the LPJ-GUESS dynamic vegetation model, while marine biogeochemistry is simulated using the PISCES ocean biogeochemical model, allowing for interactive carbon and nutrient cycling in the ocean.

Cryospheric processes are explicitly represented through the inclusion of the Parallel Ice Sheet Model (PISM), which enables interactive coupling between climate and the Greenland Ice Sheet, including feedbacks from ice-sheet mass loss to ocean circulation via freshwater input. The Antarctic Ice Sheet is not dynamically coupled; however, its contribution to freshwater fluxes under warming conditions is represented using an Antarctic Ice Melt Emulator, providing a simplified but physically constrained representation of Antarctic meltwater input.

Carbon-cycle feedbacks are closed through the simplified atmospheric CO_2 representation ("co2box"), which mediates exchanges of carbon between the atmosphere, land, and ocean reservoirs, thereby enabling a consistent treatment of carbon–climate feedbacks at the Earth system scale.

2.2 The experiments

The proposed work aims to complement existing simulations performed within TIPMIP-OCEAN by conducting additional idealised freshwater hosing experiments with EC-Earth3-ESM. These experiments systematically explore AMOC sensitivity across a range of freshwater hosing strengths between 0.3 Sv and 3.0 Sv, with the objective of identifying the transition between reversible and irreversible circulation responses.

Two experimental tiers are considered.

A. Tier 1 experiments are initialised from pre-industrial equilibrium conditions and forced with pre-industrial boundary conditions. We propose four 150-years long simulations (total of 600 model years), following two sequential phases:

- A1 (Hosing phase, 50 years): a constant freshwater flux of magnitude X Sv is uniformly applied over the North Atlantic and Arctic region, spanning from 50°N in the Atlantic to the Bering Strait. The freshwater input is globally compensated by a uniform salinity correction across the global ocean in order to conserve total ocean salinity and minimise long-term drift.
- A2 (Recovery phase, 100 years): starting from year 50 of A1, the freshwater hosing is removed and the system is allowed to evolve freely in order to assess AMOC recovery.

A set of four hosing strengths (X) will be explored, spanning the range 0.3–3.0 Sv. The initial simulation will be performed with X = 1.0 Sv, and the remaining values will be refined iteratively based on the diagnosed AMOC response, in order to better resolve the threshold region.

B. Tier 2 experiments (total of 600 model years) follow the same experimental design than Tier 1 but are initialised from a climate state corresponding to a +2°C global warming relative to pre-industrial conditions. This allows assessment of how background climate change modifies AMOC stability and hysteresis behaviour.

3. Justification for the resources requested

The simulations will be carried out in two phases: Tier 1 during the first project year (2027) and Tier 2 during the second project year (2028). Each experimental set consists of a 600-year fully coupled Earth System Model integration, resulting in a total of 1,200 simulated model years over the full project duration.

Based on previous production runs with EC-Earth3-ESM on the ATOS system using an equivalent model configuration, the computational cost is estimated at approximately 40,000 SBU per model year. This estimate includes the full coupled atmosphere–ocean–sea ice–land–carbon cycle system at standard CMIP6 resolution. Accordingly, each 600-year experiment requires approximately 24 million SBU, leading to a total computational demand of approximately 48 million SBU for the complete set of simulations. 1 million is added per year for testing, post-processing and analysis.

In terms of data output, and following the standard TIPMIP-OCEAN data request across all Earth system components (atmosphere, ocean, sea ice, land surface, and biogeochemistry), the expected storage requirement is approximately 80 GB per model year of raw output. For the full suite of simulations (1,200 model years), this corresponds to a total storage demand of approximately 96 TB. Storage allocation will be distributed evenly across the two project years to ensure balanced data handling and processing.

References

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